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Ch. 37, Inertial Fusion Energy Technology

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Auspices Statement

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Inertial Fusion Energy Technology

Energy Requirements

Providing for the world's growing energy needs is one of the most urgent, and difficult, challenges facing us. Today, approximately 80% of the world's 6.8 billion people (or about 5.4 billion) consume less than 20% of the world's total energy use of about 450 quads. Not only is the world population expected to nearly double over the next 100–150 years, but the per capita energy use of those 5.4 billion low-energy users, as well as the additional 4 billion new consumers, is likely to increase three or four times as they move up the economic ladder.

Even a world per capita energy consumption only half of today's United States per capita energy consumption would result in a fivefold increase in the world's energy consumption by the early part of the next century. Similarly, worldwide electric power demand is expected to increase significantly, doubling from its current level of about two trillion watts (2 TW) to 4 TW by 2030 and possibly reaching 10 to 15 TW by the early part of the next century. It is estimated that as many as 10,000 new one-gigawatt power plants will be needed to keep up with this growing demand.

A significant portion of the ever-increasing need for energy will likely be met by fossil-fuel sources. However, the environmental effects of that many additional fossil-fuel plants are likely to be devastating. Clearly, carbon-free sources will have to be aggressively researched and developed to help meet the demand and limit the strain on the environment.

Fusion as Part of a Global Energy Strategy

Nuclear fission, nuclear fusion, and renewable energy (including biofuels) are the only energy sources capable of satisfying the Earth's need for power for the next century and beyond without the negative environmental impacts of fossil fuels. Substantially increasing the use of nuclear fission and renewable energy now could help reduce dependency on fossil fuels, but nuclear fusion has the potential of becoming the ultimate base-load energy source. Fusion is an attractive fuel source because it is virtually inexhaustible, widely available, and lacks proliferation concerns. It also has a greatly reduced waste impact, and no danger of runaway reactions or meltdowns. The substantial environmental, commercial, and security benefits of fusion continue to motivate the research needed to make fusion power a reality.

Replicating the fusion reactions that power the sun and stars to meet Earth's energy needs has been a long-sought scientific and engineering challenge. In fact, this technological challenge is arguably the most difficult ever undertaken. Even after roughly 60 years of worldwide research, much more remains to be learned. The magnitude of the task has caused some to declare that fusion is 20 years away, and always will be. This glib criticism ignores the enormous progress that has occurred during those decades, progress in both scientific understanding and essential technologies that has enabled experiments producing significant amounts of fusion energy. For example, more than 15 megawatts of fusion power was produced in a pulse of about half a second. Practical fusion power plants will need to produce higher powers averaged over much longer periods of time. In addition, the most efficient experiments to date have required using about 50 percent more energy than the resulting fusion reaction generated. That is, there was no net energy gain, which is essential if fusion energy is to be a viable source of electricity.

The simplest fusion fuels, the heavy isotopes of hydrogen (deuterium and tritium), are derived from water and the metal lithium, a relatively abundant resource. The fuels are virtually inexhaustible and they are available worldwide. Deuterium from one gallon of seawater would provide the equivalent energy of 300 gallons of gasoline, or over a half ton of coal. This energy is released when deuterium and tritium nuclei are fused together to form a helium nucleus and a neutron. The neutron is used to breed tritium from lithium. The energy released is carried by the helium nucleus (3.5 MeV) and the neutron (14 MeV). The energetic helium nucleus heats the fuel, helping to sustain the fusion reaction. Once the helium cools, it is collected and becomes a useful byproduct. A fusion power plant would produce no climate-changing gases.

Approaches to Fusion Energy

The next step towards achieving the quest for fusion electrical power is demonstrating energy gain from the fusion fuel in a laboratory setting. Scientists have developed a variety of devices and systems in an effort to contain and heat the deuterium and tritium fuel to the densities and temperatures needed to sustain thermonuclear fusion reactions. Scientists are pursuing fusion along two main paths: magnetic confinement fusion (MCF) and inertial confinement fusion (ICF).

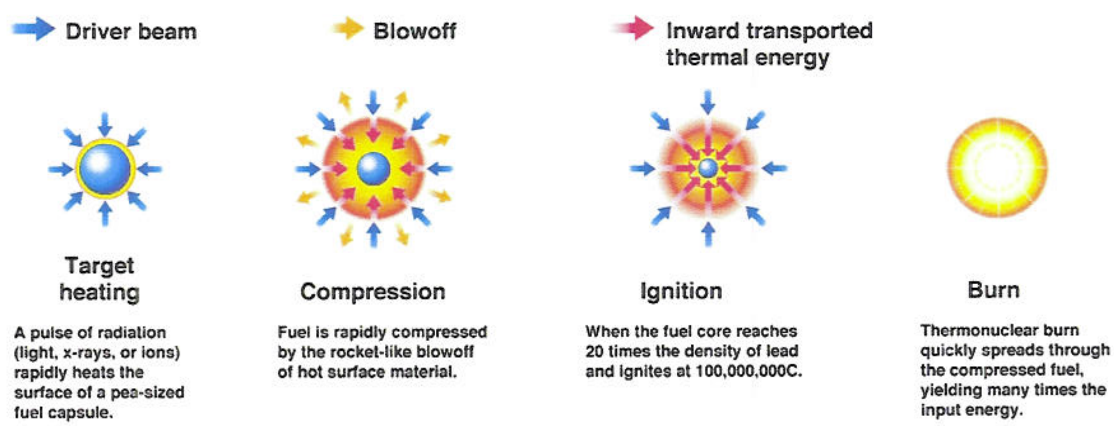
The MCF approach (see separate article on magnetic fusion energy) uses magnetic fields to confine the plasma—a hot, electrically charged gas—at the required density until it is heated to the required temperature (about 100 million degrees) for fusion reactions to occur. The magnetic field must also insulate the hot plasma sufficiently so that the energy is confined long enough to achieve net energy gain. Practical limits on the strength of magnetic fields, in turn, place upper limits on the pressure of the extremely hot fuel. As a result, the density of the hot fuel must be much less than the air we breathe. For power plants based on MCF, the burning of fusion fuel is envisioned to take place on a continuous basis, or at least in a series of long pulses, with each one lasting hours.

The ICF approach is the focus of this chapter. It uses the inertia associated with the mass of the fuel to replace the need for a magnetic field. For this approach to work, a small capsule of fuel needs to be compressed to more than 100 times solid density before the fuel is ignited. The inertia of the fuel delays the expansion just long enough (a few nanoseconds) to allow sufficient fuel to fuse and yield energy gain. No magnetic field is needed to hold or insulate this plasma. However, these little explosions must be repeated often enough to provide a continuous source of heat.

Path to Fusion Energy through Inertial Confinement

The inertial confinement approach to fusion involves rapidly compressing a tiny spherical capsule of fuel, initially a few millimeters in radius, to densities and temperatures higher than those in the core of the sun. The fuel is usually a combination of deuterium and tritium (DT) because it fuses at the lowest temperature of any fusion fuel.

To heat and compress the fuel, energy is delivered for a few nanoseconds to the outer layer of the target using some type of "driver." Three types of drivers—lasers, ion accelerators, and Z-pinches—are described later. The heated outer layer explodes outward, producing a reaction force against the remainder of the target, accelerating the target material inwards, and sending shock waves into the center. A sufficiently powerful set of shock waves can compress and heat the fuel at the center so much that fusion reactions occur. The energy released by these reactions will then heat the surrounding fuel, which may also begin to undergo fusion. The aim of ICF is to produce a condition known as ignition, where this heating process causes a chain reaction that burns a significant portion of the fuel (see Figure 1).



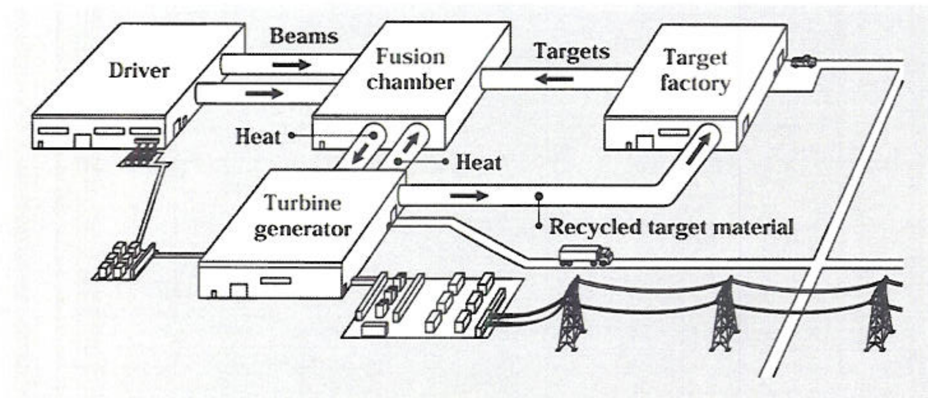
(photo credit: Lawrence Livermore National Laboratory)

Figure 1. The figure illustrates target heating, compression, ignition, and then burn.

How IFE Works

IFE operates conceptually like a car engine: fuel is injected, a piston is then used to heat and compress the fuel to the point of ignition (with the piston being a large laser or other driver), the spent fuel is exhausted, and then the cycle repeats. An IFE power plant is envisioned to have separate areas for the driver, a factory for making the targets, a chamber where the fusion reactions occur, and a conventional steam turbine to generate electricity (the portion of the IFE plant that performs the final conversion of the fusion heat to electricity is often referred to as the balance of plant, or BOP). IFE plants would deliver a successive stream of targets to the fusion chamber, and capture the resulting heat and neutron radiation from their implosion and fusion to drive the conventional steam turbine.

This separability of IFE plant components provides design flexibility and allows the driver and target factory to be protected from the fusion radiation environment. The driver must ignite a fusion target between about once every 10 seconds to several per second (depending on the driver) to produce the desired power level in the chamber. With certain driver types, a single driver could be used to operate multiple chambers by switching the final beampaths between chambers.



(photo credit: Lawrence Livermore National Laboratory)

Figure 2. Basic layout of an IFE power plant, showing the driver, target factory, fusion chamber, and turbine generator to produce electricity. The beam component would only be present for certain types of drivers.

How Much Energy is Produced in the Fusion Reaction?

Fusion-power system studies indicate that the energy released per event could range between hundreds of megajoules and several gigajoules. The corresponding repetition rates for an IFE power plant capable of producing 1000 megawatts of electricity would range from several per second to about once every ten seconds in each fusion chamber; multiple fusion chambers would be needed for some designs.

Methods of Achieving Inertial Confinement Fusion

Each ICF concept involves placing a small capsule of fuel in a chamber and then compressing and heating it to ignition conditions with some type of "driver" that generates intense pressure on the outside of the capsule. Three types of energy delivery methods, or drivers, for ICF fuel compression are presently studied: lasers, accelerators, and Z-pinches.

The physics underpinning IFE was conclusively demonstrated in a series of US and UK experiments conducted in the 1980s, laying to rest any fundamental concerns over the viability of the process. The challenge since then has been how to replicate this process using a driver that is compatible with a commercial power plant.

Decades of physics, computing, and nuclear weapons research have brought ICF technology to a pivotal point in development; ambitious ICF experimental facilities currently being built or expanded in the United States, Europe, and Japan are anticipated to propel ICF technology down the path towards commercial feasibility. Some of the projects currently underway will be discussed below.

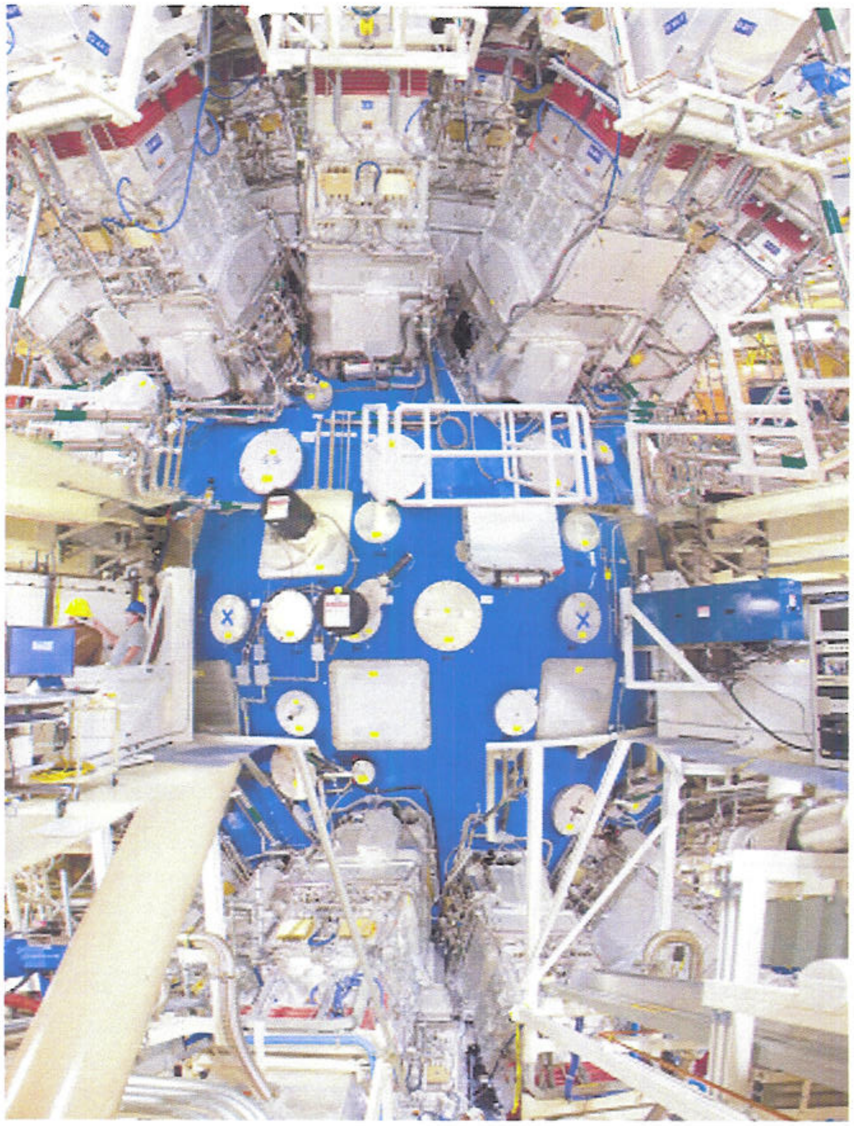
Lasers

Lasers have improved dramatically since the 1970s, scaling up in energy and power from a few joules and kilowatts to megajoules and hundreds of terawatts, using mostly frequency doubled or tripled light from neodymium glass amplifiers to focus energy on a target. Lasers are attractive because of their ability to compress energy into the very short timescales and spatial scales required to implode the fusion fuel pellet. To date, most research has focused on developing high-power lasers to study ignition, currently the most important physics issue for inertial fusion.

National Ignition Facility

The National Ignition Facility (NIF), a laser-based ICF facility designed to achieve thermonuclear fusion ignition and burn and net energy gain in the laboratory, was completed at the Lawrence Livermore National Laboratory (LLNL) in the United States in 2009. NIF's 192 giant laser beams, housed in a ten-story building the size of three football fields, deliver 60 times more energy than any previous laser system. NIF has now conducted experiments using all its beams, including experiments that set new records for power delivery by a laser. Experiments designed to pursue the NIF's ignition goal were begun in 2010, using laser energies of 1 to 1.3 MJ. Fusion yields of the order of 10 to 35 MJ (or net energy gains of 10 to 25) are expected before the end of 2012.

If successful, NIF will be the first ICF facility of any type to demonstrate ignition, and by optimizing target and laser performance, laser energies of 2.5 to 3 MJ and net energy gains of 50–70 could ultimately be demonstrated on NIF. Demonstration of ignition is considered internationally to be the seminal event that enables the transition from scientific fusion research to prototype power plant delivery. By demonstrating ignition and net gain, NIF will provide the scientific basis for future decisions regarding laser-driven inertial fusion energy research and technology development programs.



(photo credit: Lawrence Livermore National Laboratory)
Figure 3. The Nation Ignition Facility's massive target chamber (blue sphere). Notice the men wearing hard hats at the left center of the picture. The square openings and complicated ducts attached to the target chamber are the paths for NIF's 192 laser beams (four beams per duct). The round openings accommodate nearly 100 pieces of diagnostic equipment.

Laser Mégajoule

Laser Mégajoule (LMJ) is an experimental ICF facility being built near Bordeaux, in France by the French nuclear science directorate, CEA. LMJ plans to deliver about 1.8 MJ of laser power to its targets, making it similar to its US counterpart, NIF. Currently, the LMJ system is expected to commence operations in 2014. LMJ is the largest ICF experiment to be built outside the US. It uses a series of 240 laser beamlines, grouped into eight groups of 30.

How NIF and LMJ Work

NIF and LMJ use solid-state, neodymium glass amplifiers pumped by the energy from large flashlamps, delivering about 5MJ of infrared laser energy in a few-nanosecond pulse. The laser pulse is sent through the amplifiers several times by an optical switch to maximize the energy extracted and thus enhance the system efficiency. At the other end of the beamline, a deformable mirror is used to remove imperfections in the beams.

The beams are directed through an optical frequency multiplier to convert the infrared laser light into 1.8 MJ of ultraviolet light to enhance the efficiency of the fuel–pellet interaction. Just before reaching the interaction chamber, the beams are reflected off mirrors and arranged in such a way that the beams will enter the chamber from all sides to focus in the center. The beam energy coming out of the amplifiers is so high that the cross section of each beam must be kept larger than a square foot to avoid damaging the optics. As beams enter the chamber, they are focused down on the small fuel pellet. The beams hit the pellet with a precision of better than 50 microns (about the thickness of a piece of paper).

Although both facilities are designed to achieve ignition and gain, neither is designed to harness the enormous potential of fusion for energy generation. A fusion power plant, as opposed to a world-class engineering research facility, would require that the laser deliver pulses nearly 100,000 times more frequently.

(Photo credit: CEA)

Figure 4. General view of the Laser Mégajoule laser hall, where the beam amplification structures are being assembled.

Other Laser ICF Research

The NIF and LMJ have been designed and built with current solid-state laser technology, while a number of smaller, less energetic lasers are being used to study how to achieve the repetition rates and efficiencies needed for commercial fusion power generation. The high-average-power lasers approach involves research on both krypton-fluoride (KrF) gas lasers and diode-pumped solid-state lasers (DPSSL).

With the KrF laser driver, the laser medium is a gas that can be circulated for heat removal in high pulse-repetition-rate applications such as IFE. Target physics experiments are being conducted at the U.S. Naval Research Laboratory in Washington, DC using the Nike KrF laser. KrF lasers have the short wavelength and demonstrated high beam uniformity for optimum laser–target physics, the brightness to achieve the required intensity on target, a modular architecture for lower development costs, and a pulsed power-based industrial technology that scales to a power-plant-sized system.

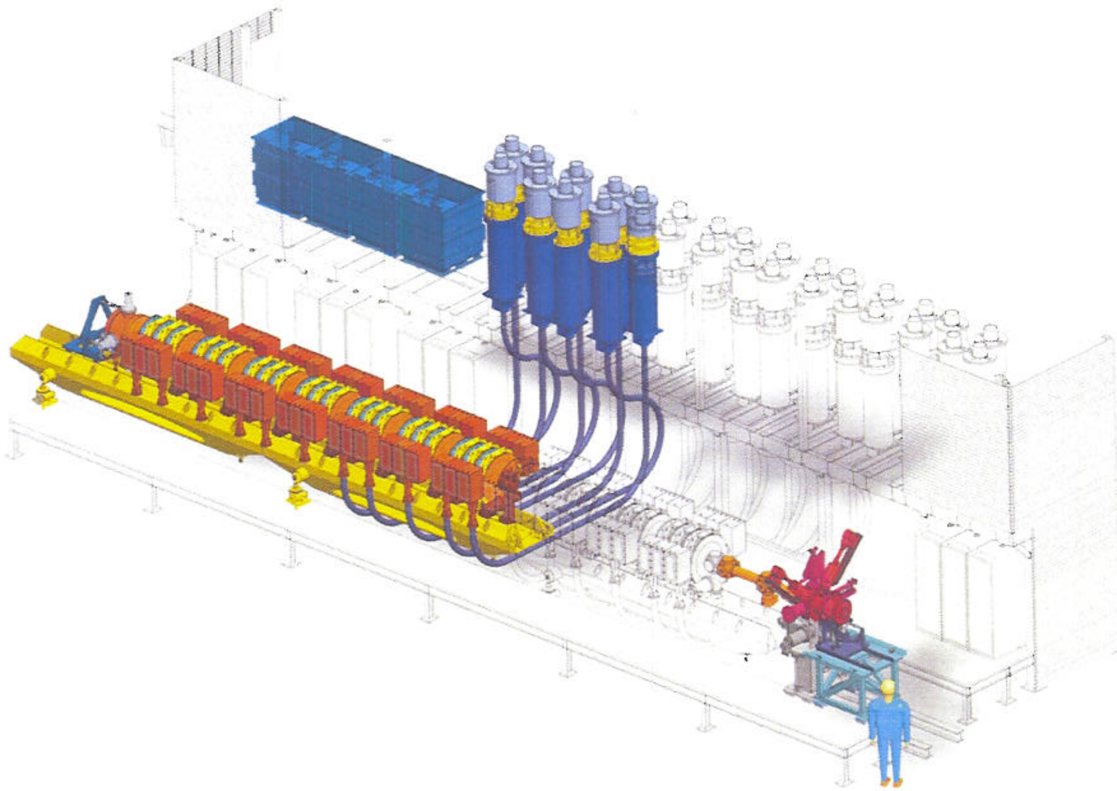
DPSSLs, which build on NIF laser technology, use diodes instead of flashlamps to pump a solid-state laser, dramatically decreasing the cool-down time needed between laser firings. LLNL's Mercury laser, for example, is a prototype DPSSL capable of scaling in aperture to a NIF-like beamline, while still running at a repetition rate 100,000 times greater. DPSSLs may ultimately improve the efficiency, pulse rate, and cost of solid-state lasers enough to enable their use as fusion power plant drivers.

Both the European Union (with HiPER) and Japan (with FIREX) are developing plans to aggressively pursue research on laser-driven ICF as an energy option. FIREX is scheduled to start ICF experiments in the 2011 to 2012 timeframe, while construction of the HiPER facility is envisioned to begin around 2015, with operation in the early 2020s. LMJ and NIF are focusing on achieving fusion ignition in the laboratory. FIREX and HiPER will demonstrate more experimental and more efficient fusion technology, as the focus shifts from the scientific proof-of-principle stage towards creation of a commercial fusion reactor.

Accelerators

Heavy-ion (HI) drivers for fusion share the same basic technology as existing accelerators used for a range of scientific and engineering pursuits. In this approach, magnetic lenses outside the target chamber are used to focus powerful and energetic beams of heavy ions on the target. U.S. researchers are developing designs that use induction accelerators, while European and Japanese groups prefer radio-frequency accelerators, similar to those used in high-energy physics. To manage the significant excess electric charge of the ions, U.S. conceptual designs accelerate many beams in parallel, and Europeans plan to accumulate charge gradually in a series of storage rings. Both approaches also require the beam duration to be severely reduced from its initial value, by about three orders of magnitude for induction machines and six for radio-frequency accelerators. The present research is primarily directed toward meeting these stringent requirements.

HI drivers are the IFE approach supported by the U.S. Department of Energy Office of Fusion Energy Science. Worldwide experience with high-energy accelerators has long supported the prospect that an HI accelerator driver can achieve the necessary efficiency, pulse rate, and durability for commercial energy generation. Heavy ion beams are particularly appealing because they are easy to create, control, and focus. On the downside, it is very difficult to achieve the very high energy densities required to implode a target efficiently.

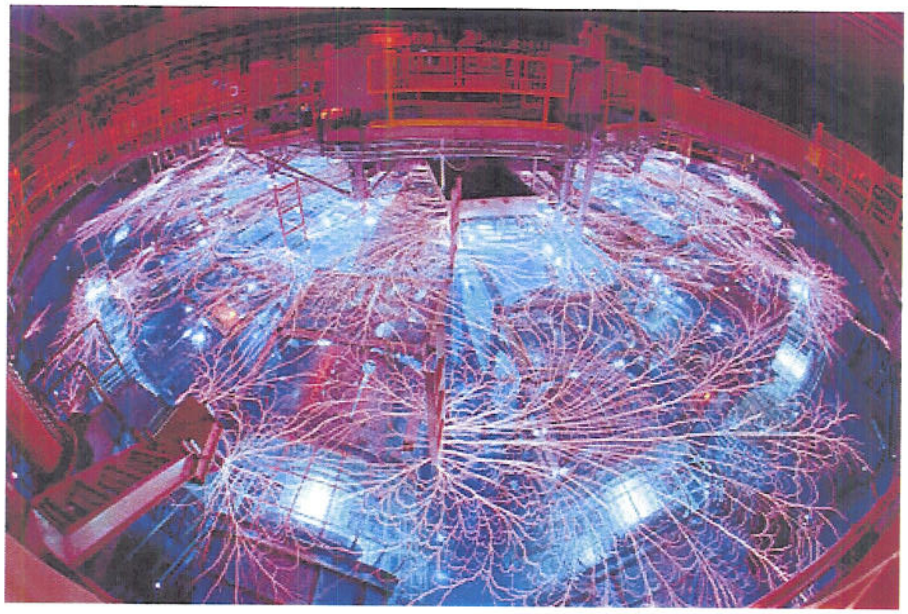


(Photo credit: Lawrence Berkeley National Laboratory)

Figure 5. Sketch of the Neutralized Drift Compression Experiment-II, an energy-efficient induction accelerator under development at the Lawrence Berkeley National Laboratory. Transmission lines for creating high-voltage pulses power the accelerator cells are in dark blue, at the top. Beam-neutralizing plasma injectors and the chamber that focuses the beam on the target are shown in orange and red at the right.

Z-Pinch

A third type of driver for ICF is the "Z-pinch," which is under development at Sandia National Laboratories in the United States, and other facilities worldwide. Z-pinch uses a cylindrical array of very fine tungsten wires and a gigantic capacitor, a device that can store and instantaneously discharge huge electric charges. When the capacitor is fired, it sends a current of 20 million amperes through the fine wires in the Z-pinch, and the wires are converted into super-hot plasma. The wires heat and vaporize so quickly that they fill the target with x rays, which implode the fuel capsule. To direct the x rays onto the capsule, the target consists of a cylindrical metal enclosure, or hohlraum, containing both the wiring and fuel. The Z-pinch driver, unlike the other ICF approaches, is physically connected to the target by transmission lines. Lower repetition rates than laser- or accelerator-driven ICF, and thus higher fusion yields per target, are envisioned to allow for replacing the transmission lines on each shot.



(Photo credit: Sandia National Laboratory)

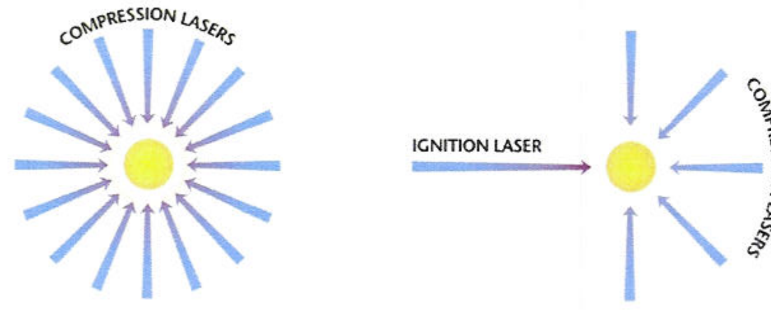
Figure 6. Sandia National Laboratory's Z-pinch device, the Z machine, in action.

Fast Ignition

In the conventional approach to inertial confinement, the drivers that compress the fuel capsule also heat it to ignition. Fast ignition, which was first proposed by Max Tabak of the Lawrence Livermore National Laboratory in the U.S., decouples the compression and heating phases of the implosion. Fast ignition, if successful, could require less driver energy than the conventional approach, which could make fusion energy production more economically attractive.

The fast ignition concept uses one of the drivers (ion accelerator, laser, or Z-pinch) to compress the target, and then uses an extremely intense laser beam to ignite a propagating thermonuclear burn wave in the compressed, but cold, target. The technique relies on the extremely short pulse (~10 ps) of a petawatt laser to heat and ignite a small portion of the fuel near the edge of the compressed capsule. This concept has the potential of increasing target gain and/or relaxing the constraints on chamber and driver specifications because no central hot spot is required. The concept is at an early stage of investigation, with complex physics and engineering issues still to solve.

The fast ignition approach was first studied at the GEKKO XII laser at Osaka University in Japan in 2001, working with a team of U.K. scientists. Several projects are currently underway to explore the fast ignition approach, including upgrades to the OMEGA laser at the University of Rochester, the GEKKO XII device in Japan (where the FIREX1 construction project is adding a powerful laser to GEKKO for fast ignition research), and an entirely new facility, known as HiPER, to be constructed in the European Union starting around 2015. If successful, the fast ignition approach could dramatically lower the total amount of energy that needs to be delivered to the target; the HiPER design, for example, will use much smaller lasers than conventional designs, yet produce fusion power outputs of similar magnitude.



(photo credit: Lawrence Livermore National Laboratory)

Figure 7. The left figure shows the symmetrical arrangement of lasers for compressing and heating a target for convention inertial confinement fusion. The right figure illustrates how, in fast ignition, the compression and heating of the target are performed by separate drivers, with different timing and geometry.

Key Considerations for a Fusion Power Plant

As researchers develop concepts for IFE power plants, they are mindful of the need to develop safe and environmentally acceptable sources of energy. Use of low-activation materials and design options such as a thick liquid wall chamber can minimize the production of activated material over the life of the plant. Control of tritium will be important for any type of fusion power plant, since its release dominates the outcomes in analyses of hypothetical accident scenarios.

Following industry best practice, a fusion power plant must meet a number of top-level requirements consistent with commercial operation. These include standardized, proven technology, maintainability and constructability, a high level of quality assurance, competitive economics, and environmental sustainability. For IFE, this translates into the need to improve performance in the following four areas:

1. **High Energy Gain and Efficiency**: The efficiency of the driver in converting energy from the electrical power grid to the energy needed to compress the capsule, coupled with the energy gain of the capsule (ratio of energy released to the energy needed to compress and heat the fuel), must be sufficient to yield substantial net energy. Generally, the product of capsule energy gain and driver efficiency must be about 10 or greater for acceptable power plant economics. As a result, the fusion energy output must be roughly 50–140 times greater than the driver energy input, depending on the 7% to 20% efficiencies projected for the various drivers.
2. **Repetition Rate**: The driver, target (which includes the fuel capsule) fabrication, and reaction chamber must operate at a repetition rate that is sufficient to produce economically useful power. The chamber must be restored to a sufficiently inactive state after each shot to allow insertion of the next target, and for the transmission and focusing of the next pulse of energy from the driver to that target. The driver needs to have a 0.1 to 10 Hz repetition rate, depending on the driver. For the high

repetition rate laser and HI driver designs, the targets would need to cost about 25¢ each or less to produce and would be made at a rate of roughly 100 million per year. The lower repetition rates envisioned for Z-pinch driven systems would allow for higher costs of the target and the transmission lines that would need to be replaced each shot. For these Z-pinch systems, around ten fusion chambers would be needed for a 1-GWe plant. While laser and HI driven systems do not have to replace transmission lines each shot, they do have the challenge of protecting or replacing the "final optics" that are exposed, to some extent, to the debris and radiation from each ignited target. The final optics are the magnets or optical components on the fusion chamber that provide the precision focusing and aiming of the HI beams or laser beams onto the target.

3. **Energy Conversion and Tritium Breeding**: The energy released from the burning deuterium tritium fuel is mainly in the form of energetic ions, neutrons, and x rays. This energy must be absorbed by the chamber and converted into heat that can be efficiently used to drive electric generators. The chamber must also use the emitted neutrons to breed sufficient new tritium (from lithium) to sustain the fuel supply.

4. **Durability and Reliability:** The components in an IFE system must carry out the above functions with sufficient durability for the high capacity factors required in an attractive energy system. The fusion chamber, for example, would need to work effectively for up to 30 years. Reliable automated systems must be engineered to replace any components that have a short working lifetime. All the major plant components and systems must operate consistently and reliably, for a better than 95% overall availability.

This complex set of interrelated performance requirements presents major challenges to the scientists and engineers dedicated to demonstrating IFE as an attractive energy source. Each of the three drivers being studied leads to complete fusion systems with different potential advantages and challenges. Many experimental facilities, both large and small, are being used to study and test the materials, components, and systems. In addition, fusion system studies help guide the research by pointing out opportunities and problem areas. As understanding and demonstrated performance progress, the potential of the various approaches can be assessed with more certainty, and the details of a demonstration power plant design will become clearer.

Fusion Plant Components

An advantage of IFE compared to magnetic fusion is that, at least in the early stages, the power plant subsystems (described below) can be developed and tested separately and often at lower cost than fully integrated facilities. Even the driver itself is modular, or composed of modular parts, allowing researchers to work out many problems on scaled-down versions before moving to a more expensive full-scale device. While the separability should also have long-term advantages, such as producing lower operational costs (due to ease of replacing worn-out parts) and enabling gradual improvements as technology matures, it does not eliminate the sizable challenge of making all the individually tested and proven components work together smoothly. The IFE power plant ultimately requires successful integration of all the components, with an understanding of the system interfaces and the impact of design choices for one system on the others. As such, system-level studies are used to guide the research by highlighting opportunities and problem areas. Full-scale demonstration IFE plants will be the true test for integration.

Some of the essential requirements for IFE plant components are discussed below.

High Repetition Rate Driver

When the above performance measures are applied to drivers, they place constraints not only on the repetition rate, reliability, and efficiency of energy delivered to a high-gain target, but also on the capital cost of the driver. System studies indicate that this capital cost should be less than about $400 per joule of energy delivered to the target, depending on the specific driver characteristics and associated target gain. As mentioned earlier, fast ignition, or other advanced techniques for igniting targets with less total energy input, would either ease this constraint or enhance the economics of the plant.

The following paragraphs compare some of the characteristics of the drivers described earlier and their impact on the ability to meet the performance requirements.

KrF lasers operate at shorter wavelength (248 nm) than the typical frequency-tripled wavelength (351 nm) of the DPSSLs. This shorter wavelength allows higher intensities to be applied before triggering instabilities in the target. As a result, the required gains of 140 are predicted for less energy (1.1 MJ) delivered. This advantage is partially offset by lower predicted driver efficiency of about 7% for KrF versus 10% for DPSSLs. The flowing gas laser medium in a KrF laser makes it easier to cool than the glass slabs in a DPSSL. Faster cooling makes it easier to achieve the required repetition rates of 5 to 10 Hz. However, progress continues on the DPSSL repetition rate issue using new laser architectures. Another repetition rate challenge for the DPSSL approach is the development of a high-average-power frequency converter to 351 nm light. Costs for diode arrays for the DPSSL are high but have been decreasing as more are produced. Progress on durability issues for different components in KrF and DPSSL also continues. For the KrF, the goal is two years of continuous operation at 5 Hz. The diode arrays for a DPSSL are projected to last 30 years at 10 Hz.

Final optics present a durability issue for both the KrF and DPSSL. In both systems, these optics must survive the high intensity UV of the laser beam, and the debris, neutrons, and x-ray radiation from the exploding target. One approach uses grazing incidence metal mirrors. Aluminum-coated silicon carbide is one of the types being considered.

The HI accelerator approach is based on technologies developed for other high-power accelerator applications. This experience indicates that an HI driver could meet the efficiency, repetition rate, and durability performance measures. In addition, the penetration of HIs into dense matter is greater than UV or x-ray photons. This feature yields more efficient energy coupling to the target. It also allows more efficient penetration through the higher vapor pressures in the target chamber than would occur if liquid thick-walled blankets were to be used (see target chamber, below). These features could result in comparatively low capital costs.

A major challenge for the HI approach is to demonstrate the ability to focus an energetic (10 KJ) beam onto a target with the required short-pulse length (few ns) and small spot size (few mm radius). As described above, much of the present research is devoted to achieving the high intensity, sufficiently bright beams that will be necessary, and then shortening them by large factors by carefully ramping the velocity of the beam particles from the front of the pulse to the rear. If the beam temperature is kept low enough, such a scheme could shorten the pulse to the desired duration by the time the pulse reaches the target. The final optics for an HI system would be steering and focusing magnets on the chamber. Shielding these magnets from debris and x-ray radiation should be straightforward. Balancing performance and neutron shielding properly are expected to allow these magnets to have adequate lifetimes.

The Z-pinch approach offers the potential for the highest driver efficiency of those being studied. Experiments on Sandia Laboratory's Z machine demonstrated 15% efficiency in converting electrical energy to x rays. Recent designs based on linear transformer driver technology offer high repetition rates, greater reliability, and twice the efficiency of the Marx generator technology on Z. A recyclable transmission line (RTL) connects the driver to the capsule, eliminating final optics, beam focusing, and target tracking issues. This also allows the use of thick liquid blankets to protect the chamber wall. However, the technology requires the replacement of the RTL every ten seconds, which presents a substantial technical and cost challenge.

The lower repetition rate (0.1 Hz) in the Z-pinch approach is compensated by increasing the yield per pulse by 10-fold, and by having 8 to 10 fusion chambers operating together in a 1-GWe power plant. The chambers need to be designed to handle these higher yields and the longer times between pulses of heat.

Fusion Chamber

Each fusion target releases a burst of fusion energy in the form of high-energy neutrons (about 70% of the energy), x rays, and energetic ions. The fusion chamber must contain this blast of energy and convert the sequences of energy pulses into a steady flow of power for the power conversion system. Reactor studies call for capturing the neutrons in a "blanket" that contains lithium surrounding the hot plasma fuel. The neutrons, x rays, and other products from the exploding target would heat the blanket, and this heat would be transferred to a steam boiler to power a conventional turbine. The neutrons would also interact with the lithium to "breed" more tritium fuel. The blanket and some other internal components of the reactor may need to be replaced periodically, depending on the design. The main part of the fusion chamber would be spared the damage from the radiation and debris.

Another consideration for the chamber is the survival of the innermost wall (first wall) that is exposed to intense heat and radiation from the target's energy release. Various chamber designs have been proposed and fall into three major classes:

- Dry wall, where the innermost surface is a solid material such as tungsten designed to handle the full target energy impact.
- Wetted wall, where a thin liquid layer coats the first wall and absorbs the short-range x rays and ions before they can damage the wall.

- Thick liquid wall, where more than 50 centimeters of liquid (lithium-bearing metal or molten salt) flows between the target and first wall and provides protection from x rays, ions, and neutrons.

Not only must the chamber survive the repeated energetic bombardments during fusion reactions, it must also effectively manage the intra-shot recovery—the conditions inside the chamber (such as vapor and droplet density) that must be recovered between each shot to the point that the next target can be injected and the laser or HI beams can propagate through the chamber to the target. In the case of the Z-pinch, the transmission line and new target need to be installed and readied for the next electrical pulse during this period.

At a basic level, the chamber and blanket must keep the radioactivity low to ensure worker safety and avoid the necessity of high-level waste disposal. Finally, the blanket must operate at temperatures of more than 500 degrees Celsius in order to achieve high efficiency in the power conversion system, and the tritium bred in the blanket must be extracted.

Target Injection and Tracking

A key technical challenge is developing the process for injecting fusion targets into the center of the target chamber at 5 to 10 times per second, and then tracking them in flight for precise engagement by multiple drivers. In LMJ and NIF, targets are held in place at the center of the chamber and the beams are aligned to the ideal fixed position for each laser shot. For IFE laser- and HI-driven plants, targets will have to be injected at speeds greater than 100 meters a second and tracked in flight to provide data to a real-time beam-pointing system needed to ensure the precise illumination required to achieve ignition and high energy gain.

Target injection, steering, tracking, and engagement can be demonstrated with surrogate targets and low-power lasers or HI beams in separate facilities. Target injection experiments using gas guns have been conducted at General Atomics in San Diego, California, with room-temperature surrogates. Conceptual designs for other types of injectors, such as electromagnetic accelerators, and for target tracking and beam pointing systems have also been completed.

The Z-pinch faces the different challenge of replacing the transmission lines in contact with the target that are destroyed with each shot; however, Z-pinch is expected to compensate for a slower repetition rate with higher per-shot power production.

Power Conversion System

By flowing a coolant through the fusion chamber at a steady rate, the pulsed fusion energy can be extracted at a constant rate and delivered to the power conversion system, which converts the thermal power to electric power. When liquids such as lithium, lead-lithium alloys, or the molten fluorine-lithium-beryllium molten salt known as flibe are used for tritium breeding, the liquid is generally circulated as the primary coolant for the fusion chamber. When solid breeders such as lithium-aluminate are used, high-pressure helium serves as the chamber coolant. In either case, the primary coolant circulates through heat exchangers that power electric power equipment. The efficiency of the power conversion systems depends on the outlet temperature of the primary coolant, which is limited by the materials used in the construction of the blanket and chamber. With advanced material being developed for fusion and other applications, conversion efficiencies of 40 to 50 percent should be possible. Some work has also been done on ideas for converting a portion of the target energy output directly to electricity.

Target Factory

The target factory must produce a continuous supply of high-quality targets at an acceptable cost—typically 25¢ for a target that produces 300 megajoules of energy. Many types of targets are being considered for IFE, including indirect drive (like those being shot on NIF), direct drive (currently being tested on the OMEGA laser at the University of Rochester), and advanced designs such as fast ignition. In all cases, the fusion fuel is contained in a spherical fuel capsule. Near-term experiments planned for NIF will use capsules made of plastic, beryllium, carbon, or carbon-hydrogen polymers, but for IFE plants, it is likely that polymer capsules will be the preferred material. The fuel capsule must be cold enough for deuterium-tritium fuel to freeze and form a layer of ice on the inner wall of the capsule.

For direct-drive targets, the capsule is directly and symmetrically irradiated by the laser or HI beams. For indirect-drive targets, the capsule is placed inside a hohlraum, a tiny, can-shaped container made with high-atomic-mass materials like gold and lead with holes at each end for laser beam entry. In the case of HI, the holes are not needed because of the longer penetration depth of HI beams. If the power plant operates at five shots a second, the target factory will have to produce more than 400,000 targets a day.

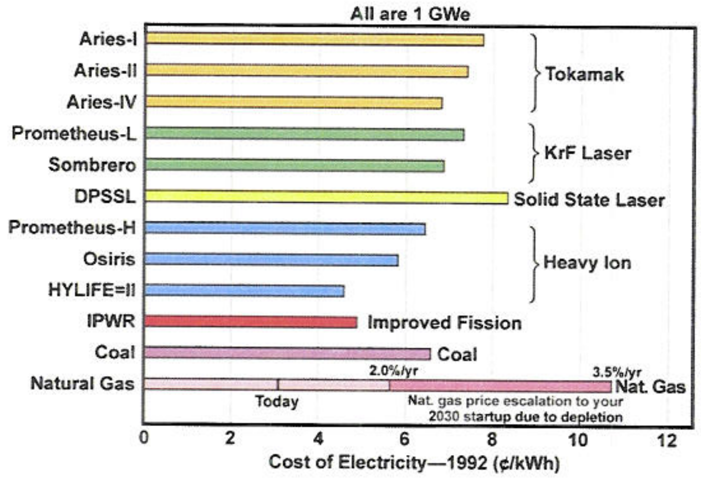
LLNL materials science experts, working with General Atomics in San Diego, California, have shown that fully automated, low-cost, large-volume target manufacturing can be adapted from the food and beverage and other mass-production industries. Researchers have begun using existing modeling codes for NIF fusion targets to design precise, low-cost fusion targets for IFE plant concepts that would be scalable to mass production.

Sandia Laboratory is studying the best indirect drive target designs to ensure efficient and repeatable coupling of electrical energy to x rays and then to capsule implosion. It is also studying how to mass produce these targets and the attached recyclable transmission lines in a way that minimizes material inventory and cost.

Target Performance

For IFE, a target gain greater than about 100 is needed in order to minimize the portion of generated electric power that has to be recirculated within the plant to operate the laser. Fast ignition targets are expected to give gains of several hundred. A lower recirculating power fraction would result in more power being available for sale, so the cost of electricity would be lower. Most target physics issues can be studied and resolved using existing technologies and facilities such as NIF and the Z machine. However, studying some technologies will require new or upgraded facilities, such as for HI targets and fast ignition targets.

How much would IFE power cost?



(Photo credit: U.S. Department of Energy programs)

Figure 8. The projected cost of several laser- and accelerator-driven IFE power plant concepts compares favorably with other long-term energy options, primarily because of cheap and stable fusion fuel prices.

Economic models based on experience with NIF, coupled with industry-standard models, show that inertial fusion energy would be highly cost-competitive with alternate sources of low-carbon baseload electricity. These models provide price requirements for the consumable elements (fuel pellets, optics, etc.), and guide the path to implementation. An important aspect of fusion energy, in contrast with many other energy sources, is that the cost of production is inelastic. In the case of wind energy, for example, the first wind farms are built in ideal locations for maximum efficiency. Later wind farms must build in less suitable locations—possibly competing with other land use needs or in locations far from energy demand—and thus for higher costs. With fusion energy, the production cost of plants will not increase significantly as more plants are built. Since the fusion fuel itself is derived from abundant, readily available materials, the fuel prices will remain stable and affordable, as fossil and fission fuel prices rise precipitously.

Fusion–Fission Hybrids

Approaches for the use of fusion–fission hybrids for power generation have been discussed since the 1970s. These approaches were originally considered as a means to breed fuel for fission reactors. More recently, scientists have begun to explore the possibility of combining fusion and fission to generate electricity while at the same time disposing of nuclear waste.

One such concept now under study at LLNL is the Laser Inertial Fusion Energy, or LIFE, concept, which would use a solid-state laser driver. The proposed LIFE power plant could be configured as a pure fusion IFE plant or be surrounded by a subcritical fission blanket to function as a hybrid plant. In a LIFE power plant, a laser focused on very small fuel capsules would produce about 500–2000 megawatts of fusion power. The fusion process also generates high-energy neutrons that, in the hybrid plant design, bombard a blanket of fertile or fission fuel. The blanket's fissile reactions multiply the energy from the fusion process and produce the heat that is used to drive turbines similar to those in current electrical power plants, generating safe, environmentally friendly power. The fuel could be thorium, light-water reactor spent nuclear fuel, weapons-grade plutonium, highly enriched uranium, or natural and depleted uranium. Using leftover fuels such as these, LIFE could supply U.S. electricity needs for more than 1,000 years.

The fusion source of neutrons allows the LIFE engine to burn its fuel to more than 99 percent FIMA (fission of initial metal atoms) without refueling or reprocessing. The nuclear waste produced in this process has very low concentrations of long-lived actinides compared to the spent fuel from conventional reactors. And because the fuel is burned so completely, LIFE engines could reduce the quantity of spent fission fuel destined for long-term underground storage by a factor of 15 to 20 per unit of energy generated.

Such a hybrid reactor would operate at a substantially sub-critical state, so that the fissile fuel in a LIFE engine could not spontaneously generate enough neutrons to start or maintain a nuclear chain reaction. This could ease regulatory requirements, reduce development and implementation costs and delays, and make the technology more attractive to private industry.

Depending on how it is configured, a LIFE engine would require a ramp-up time of days to about two years before reaching full electrical power. If configured as a fusion–fission hybrid, the continuous power phase lasts for five to more than 40 years, followed by an incineration or burn-down phase in which nearly all actinides are converted to fission by-products.

The Future of IFE

Following decades of effort, IFE research is at a key juncture. The demonstration of fusion ignition and gain in an experimental setting will spark the transition from scientific research to the delivery of a pilot fusion plant based on the integration of the required IFE components. This will test and validate the system integration and scaling of various systems, options, and technologies, and determine what is needed to roll out a series of commercial power plants. A commercial demonstration plant would follow, illustrating the plant's reliability, availability, and maintainability, and establishing the detailed economics and licensing regime. Timescale estimates suggest that a prototype plant could be operational in the mid-2020s, with commercial rollout commencing a few years thereafter.

Renewable energy sources will be an increasing and important part of the energy portfolio over the next 100 years, as will continued emphasis on increasing the energy efficiency of our power-consuming devices. But providing for 22nd century energy demand will require that revolutionary responses be pursued in parallel with evolutionary ones. Researchers are hoping that ICF technology can take up that challenge and scale to meet future commercial energy needs.